WHEN THE DUST SETTLES: FRACTAL AGGREGATES AND PLANETESIMAL FORMATION
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In order for planetesimals to form, the microscopic solid grains originally present in the Solar Nebula had to settle to its central plane. The formation of a dense layer enriched in solid matter was necessary, either to attain a critical density for gravitational instability (Goldreich and Ward 1973), or more likely to allow growth by collisions (Weidenschilling 1995). From the earliest time it was recognized that settling of micron-sized grains was too inefficient, and that such grains had to coagulate into cm-scale aggregates in order to form such a layer (Safronov 1969). Coagulation at this scale was plausible, due to the surface forces between small particles colliding at the low velocities expected (Weidenschilling 1980).

The first numerical models of planetesimal formation (Weidenschilling 1980, Nakagawa *et al.* 1981) showed that coagulation was driven by differential settling. Larger particles, which settled faster, swept up smaller ones and grew still larger. This led to "runaway growth" and "raining out" of the largest ones on typical timescales of a few thousand orbital periods. These early models assumed that all particles, regardless of size, had the same density. It was shown that, to first order, the assumed density did not affect the computed growth rate. For spherical particles of given mass, higher density meant a smaller collision cross-section but higher settling velocity; the two effects canceled (Weidenschilling 1980).

Eventually it was realized that aggregation of solid grains would not generally produce spherical particles, but irregular shapes with variable density. Such bodies are fractals, characterized by a dimension D such that mean density varies with size s as $s^{(D-3)}$; e.g., $D = 2$ means that density is inversely proportional to size. Fractal bodies have aerodynamic properties different from compact bodies ($D = 3$); Meakin and Donn (1988) pointed out that this could affect their settling behavior in the Solar Nebula. The first attempt to include this behavior was by Weidenschilling *et al.* (1989), who used Meakin's results from computer simulations of random aggregation to model aerodynamic properties. This seemed to show a significant effect, increasing settling/growth times by an order of magnitude. However, the delay was apparently due to insufficient resolution of the mass distribution; later simulations (Weidenschilling and Cuzzi 1993) showed that fractal properties had very little effect.

Since that time, improved models of particle coagulation have been developed, using more elaborate codes to bring particles and aggregates together stochastically in computer simulations, with various criteria for sticking and restructuring in collisions (Blum *et al.* 1994, Dominik and Tielens 1997). Also, fractal aggregates have been created in the laboratory and studied in detail (Blum 1997). Most of these efforts produced aggregates with $D{\sim}2$. These results have reopened the question of the mechanism of particle growth in the nebula. It is often stated that fractals with $D \leq 2$ have uniform settling velocities, independent of their sizes. If this were strictly true, fractal structure would prevent "rainout," which depends on the settling rate increasing with size. However, aggregates with $D<2$ have mass/area ratio, hence settling velocity, that does increase with the number of constituent grains, but asymptotically approaches a limiting value at large sizes. Thus, differential settling is still a viable growth mechanism for small aggregates, but becomes less effective for larger ones. At what size does fractal structure inhibit settling? Can this effect, with plausible assumptions, delay or inhibit formation of planetesimals?

I have simulated coagulation and settling in a standardized case with different assumptions as to fractal dimension and size range for which aggregates have fractal properties. At 1 AU the nebula has gas density 3.65×10^{-9} g/cm^3 and surface density of solids 15 g/cm^2. At $t = 0$, all solids are present as grains of size 10^{-4} cm. The simulations are carried out until settling has produced a particle layer with spatial density in the central plane of $3M_{\odot}/2\pi r^3$, the classical value for gravitational instability (solids/gas mass ratio ~76 at $r = 1$ AU). Tested cases included two values of uniform density ($D = 3$), fractals with dimensions 1.95 and 2.11 from Meakin's models, and fractals corresponding to computer models of Blum *et al.* (1994) for particle-cluster aggregation (PCA) and cluster-cluster aggregation (CCA). PCA assumes grains are added singly, and produces aggregates with $D \approx 2.3$ at small sizes, but approaching constant density with ~85% void space for clusters of >1x10^4 grains. CCA yields fractals with $D \approx 2.1$ at large sizes. Blum *et al.* also provide expressions for effective collision cross-sections. Dominik and Tielens (1997) consider surface forces between grains, and show that very large fractal aggregates are subject to restructuring in collisions, so that extreme gossamer structures are unlikely. I assume fractal structure persists to some limiting size, chosen as a free parameter, above which the aggregates have uniform density.

Results are summarized in the table. With one exception, all simulations reached critical density in the central plane within a few thousand years. For D = 1.95 and limiting size 1 cm (minimum aggregate density 2x10^{-4} g/cm^3), settling was slowed so that the peak density in the central plane reached 0.75 times critical at 3500 y. At that time it began to decrease because collisional coagulation had produced large bodies, which were stirred by their mutual gravitational perturbations. Even in extreme cases, in which fractal structure is assumed to persist for aggregates comprising millions of grains, there is little effect on planetesimal formation timescales.

	Size Limit (cm)	**No. of Grains**	t_{crit} **(y)**
D = 3 ρ = 0.5	n/a	n/a	1321
ρ = 3.0	n/a	n/a	1645
D = 1.95	0.01	5x10^3	1648
	0.10	7x10^5	2118
		1x10^8	3500*
D = 2.11	0.01	1x10^4	1561
	0.10	2x10^6	1647
	1.0	2x10^8	1805
PCA (D~1.3-3)	0.002	1x10^3	1394
	0.020	1x10^5	2723
CCA (D~2.1)	0.01	3x10^4	1458
	0.10	3x10^6	3519

*Reached 0.75 times critical, then decreased.

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